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Rates, Progenitors and Cosmic Mix of Type Ia Supernovae

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ABSTRACT
Following an episode of star formation, Type Ia supernova events occur over an extended period of time, following a distribution of delay times (DDT). We critically discuss some empirically-based DDT functions that have been proposed in recent years, some favoring very early (prompt) events, other very late (tardy) ones, and therefore being mutually exclusive. We point out that in both cases the derived DDT functions are affected by dubious assumptions, and therefore there is currently no ground for claiming either a DDT strongly peaked at early times, or at late ones. Theoretical DDT functions are known to accommodate both prompt as well as late SNIa events, and can account for all available observational constraints. Recent observational evidence exists that both single degenerate and double degenerate precursors may be able of producing SNIa events. We then explore on the basis of plausible theoretical models the possible variation with cosmic time of the mix between the events produced by the two different channels, which in principle could lead to systematics effects on the SNIa properties with redshift.

Key words: supernovae: general – galaxies: evolution – galaxies: high redshift

1 INTRODUCTION

Type Ia supernovae (SNIa) play a prominent role in current cosmology and astrophysics. They have been instrumental in discovering the acceleration in the expansion of the universe (Riess et al. 1998; Perlemutter et al. 1999), are major producers of iron in galaxies and clusters of galaxies (e.g., Matteucci & Greggio 1986; Renzini 1997; Böhringer et al. 2004; Sato et al. 2007), contribute to power winds/outflows in elliptical galaxies (Ciotti et al. 1991; Ciotti & Ostriker 2007), and their precursors may contribute to the UV and soft X-ray emission from elliptical galaxies (Greggio & Renzini 1990; van den Heuvel et al. 1992).

Given the importance of SNIa's, the identification of the variety of their precursors and the evolution of their rate following an episode of star formation have become central issues whose relevance goes well beyond the field of supernova physics.

There is general agreement that SNIa events arise for the thermonuclear explosion of a white dwarf (WD) whose mass increases until explosive carbon burning is ignited. Two classical scenarios have been proposed for the SNIa precursors, which differ in the mode of WD mass increase: the so called *single degenerate* (SD) model of Whelan & Iben (1973), in which the WD accretes and burns hydrogen-rich material from a companion, and the *double degenerate* (DD) option, in which the merging of two WDs in a close binary triggers the explosion (Webbink 1984; Iben & Tutukov 1984).

For a long time there has been no direct observational evidence favoring one scenario over the other, but exciting developments have taken place recently. A radial velocity survey of ~ 1000 nearby WDs has shown that over 10% of all WDs are indeed DD systems, and that systems with a combined mass close to or exceeding the Chandrasekhar limit not only exist, but can be close enough to merge in less than one Hubble time due to the emission of gravitational waves (Napiwotzki et al. 2002, 2003). Very recent is the discovery of variable circumstellar absorption lines in the SNIa 2006X, which indicates the SD nature of its precursor (Patat et al. 2007). Finally, the tentative association of an X-Ray source near the position of (and prior to the explosion of) SNIa 2007on (Voss & Nelemans 2008), may represent the first direct detection of the precursor of a SNIa event. Since WDs that accrete and burn hydrogen are expected to be super-soft X-Ray sources, Voss & Nielemans favor the SD scenario. However, the DD scenario cannot be ruled out for this event, given that a hot (hence X-ray emitting) accretion disk is likely to be the intermediate configuration of the system, between first WD-WD Roche-lobe contact and explosion (Yoon et al. 2007). Thus, quite plausible candidates for both SD and DD scenarios exist, indicating that nature may well feed both channels (see also Parthasarathy et al. 2007).

Besides the nature of the precursors, the second critical issue concerns the evolution of the SNIa rate past an episode of star formation, which is proportional to the so-called distribution of the delay times (DDT) between the birth of the precursor and the explosion. The SD model predicts a sharp rise of the SNIa rate, starting from zero at a delay time $t \simeq 3\times10^7$ yr, reaching a maximum $\sim 10^8$ yr later, then followed by a steady decline extending for about one

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Hubble time or more (Greggio & Renzini 1983). A quite similar behavior is found in the so-called *scenario code* rendition of the DD channel (Yungelson et al. 1994), whereas Greggio (2005) has demonstrated that for a very wide range of adopted parameters a sharp rise to the maximum, followed by a (quasi) plateau lasting a few 10^8 to a few 10^9 yr, and by a steady, long-lasting decline is a generic property of both the SD and the DD models. This is illustrated in Fig 1 showing a selection of model DDTs from Greggio (2005) for both the SD and the DD cases. These distributions depend on various parameters such as the mass range of the components of the binary systems which result into a successful explosion, or the amount of orbital shrinkage during binary common envelope evolution, which affects the distribution of the separations of the DD systems at birth. For the SD model the late epoch steep decline is related to the need of securing a Chandrasekhar mass by summing the WD mass and the envelope of a progressively lower mass donor, which constrains the initial mass of the primary in a progressively narrower range. For the DD models the explosion time is set by the evolutionary timescale of the secondary plus the time taken by the DD system to merge by gravitational wave radiation, which is a strong function of the DD separation. The options DD WIDE and DD CLOSE refer to two different assumptions for the degree of orbital shrinkage during the first common envelope phase, with the DD CLOSE case favoring events with short delay times. For more details see Greggio (2005).

At present existing data do not allow a firm preference for one model over another, but we note that the behavior of their DDTs quite naturally predicts both a high rate in blue, star-forming galaxies, as well as some level of SNIa activity in red, passively evolving ellipticals (Greggio 2005), which is in fine agreement with state of the art estimates of the SNIa rate in local galaxies of various morphological types (Cappellaro, Evans & Turatto 1999; Mannucci, et al. 2005).

For a variety of astrophysical applications, conveniently simple parameterizations of the DDT function have been often adopted, such as e.g., a declining power law ($DDT \propto t^{-\alpha}$, Ciotti et al. 1991; Renzini 1997), or an exponential ($DDT \propto e^{-t/\tau}$, Madau, Della Valle & Panagia 1998). Given the growing interest on SNIa's, more empirically motivated renditions of the DDT/SNIa rate have been recently proposed which are clearly irreconciliable with each other. For example, the DDT function proposed by Strolger et al. (2004) implies no SNIa events at all during the first $\sim$ 2 Gyr, whereas $\sim$ 50% of all events would take place during the first $\sim 10^8$ yr according to the DDT function favored by Mannucci, Della Valle & Panagia (2006). These latter authors also appeal to a *bimodal* SNIa rate/DDT, with a *prompt* component (possibly) separated from a *tardy* ones, a scenario that is becoming quite popular.

In this paper we examine critically these proposed SNIa distributions of delay times, first checking their empirical basis, then discussing whether they can be reconciled (or not) with their theoretical counterparts, and whether they are consistent with other relevant evidences in a broader astrophysical context. Finally, we discuss to which extent these recent observational developments lead to progress in our understanding of the nature of SNIa precursors and the evolution of their rate through cosmic times. The current concordance cosmology is adopted, when needed ($H_\circ = 70$, Ω_M = 0.3, $\Omega_\Lambda = 0.7$).

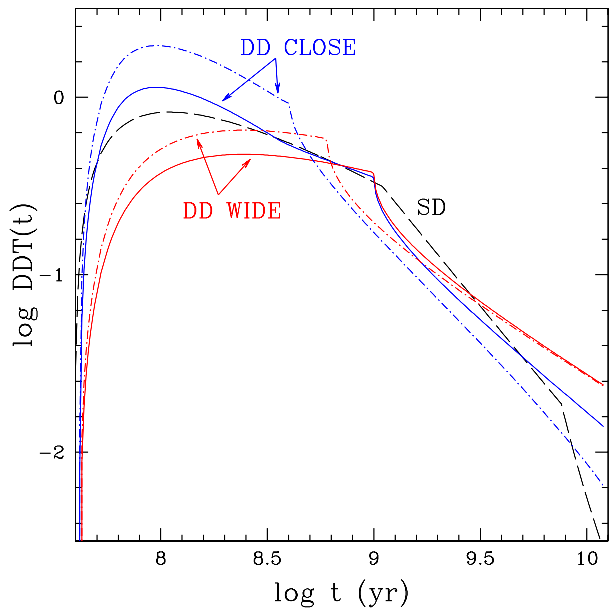

Figure 1. Examples of the distribution of SNIa delay times for the SD and the DD models, adapted from Greggio (2005). The SD model (long dashed line) assumes a flat distribution of the mass ratios of the binary progenitors, and a full efficiency of WD mass growth relative to the mass transferred by the donor. Two realizations of the DD CLOSE, and DD WIDE models are shown, all relative to a flat distribution of the separations of the DD systems. These models assume different values for the minimum mass of the secondary in the binary SNIa progenitor: 3 and 2 $M_\odot$ respectively for the dot dashed and the solid DD CLOSE cases; 2.5 $M_\odot$ and 2 $M_\odot$respectively for the dot dashed and the solid DD WIDE lines. The DDTs are normalized to 1 over the range $0.03 \leqslant t \leqslant 12$ Gyr, so to give the same total number of events.

2 DDT FUNCTION MOTIVATED BY THE REDSHIFT EVOLUTION OF THE SNIA RATE

Strolger et al. (2004, 2005) have proposed for the DDT function a Gaussian peaking at t = 3.4 Gyr after the birth of the star progenitors, with σ = 0.68 Gyr, which has virtually no SNIa events during the first $\sim$ 2 Gyr, i.e., a scenario lacking completely the *prompt* events. This result is at macroscopic variance with theoretically-motivated DDT functions, as well as with other empirically motivated functions to be discussed in the next sections. In particular, such a Gaussian function cannot reproduce the trend of SNIa rate with galaxy type/colour, which is highest in actively star-forming galaxies (Greggio 2005; Mannucci et al. 2006; Sullivan et al. 2006). For these reasons, we re-discuss here this result and its empirical basis.

Strolger et al. DDT function is based on the SNIa rates as function of redshift derived by Dahlen et al. (2004) from the supernova survey spin-off of the GOODS project (Giavalisco et al. 2004). The mentioned Gaussian DDT is a consequence of the high peak of the SNIa rate at $z \sim 0.8$, followed by its sharp drop at $z > 1.4$. The height of the peak, first confirmed by Barris and Tonry (2006), has been later questioned by other measurements. Actually, in the current literature there is a large discrepancy between the estimates of the SNIa rate at z between 0.5 and 0.8 (see recent compilation in Blanc and Greggio 2008), with other determinations lying formally more than $\sim 2\sigma$ below the SNIa rates of Barris and Tonry (2006) and Dahlen et al. (2004). If the latter measurements are excluded,

the observed trend of the SNIa rate with redshift can be well accounted for with wide DDTs encompassing both prompt and tardy events such as those shown in Fig. 1 (Botticella et al. 2008, Blanc and Greggio 2008).

However, it is the low rate at $z = 1.6$ measured by Dahlen et al. (see also Poznanski et al. 2007 and Kuznetsova et al. 2008) that basically requires setting to zero the DDT function for $t \lesssim 2$ Gyr, hence dropping completely the *prompt* events. In Dahlen et al. the data point at $z = 1.6$ is derived from just 2 events (3 events in Poznanski et al. 2007, but with more uncertain redshifts), indeed a regime of small number statistics. However, somewhat more statistically significant are the *missing* events that would be expected from DDT functions that peak at $t \sim 10^8$ yr, such as those e.g., shown in Fig. 1. Scaled to the Dahlen et al. sample, these DDT functions would predict $\sim 4-6$ events in the $z = 1.6$ redshift bin, whereas only 2 are observed.

One critical assumption in Dahlen et al. concerns the extinction, for which $E(B-V) = 0.15$ is adopted for all galaxies and all redshifts. However, as pointed out by e.g., Mannucci, Della Valle & Panagia (2007), star forming galaxies at high redshift are likely to be affected by higher extinction than local ones, an issue we quantify below. Indeed, extinction must become more and more important at higher and higher redshifts for several reasons:

- Supernovae are discovered on one-band images, hence sampling shorter rest-frame wavelengths the higher the redshift. Thus, the higher the redshift, the stronger the extinction in the rest frame band, since extinction increases with decreasing wavelength, such as in the extinction law of Calzetti et al. (2000) for which $A_V = 4 \times E(B-V)$, and $A_{1500} = 10 \times E(B-V)$. In the case of the HST/GOODS survey, supernovae are discovered on z-band (F850LP) images, hence sampling the rest frame ~ 5700 Å at $z = 0.5$, ~ 4200 Å at $z = 1$ and ~ 3200 Å at $z = 1.6$.

- In a given SN survey, the extinction correction has a relatively small effect at low redshift, since events are quite bright and discovered well above the magnitude limit for detection. Instead, the effect of extinction increases with redshift as events approach the detection limit, and becomes dominant near the limit redshift reached by the survey. In this way, an underestimate of the extinction (assumed independent of redshift) will have only a modest effect on the estimated SN rate at low redshift, but will have a very large effect near the redshift limit of the survey, both because the extinction correction is largest at the shortest wavelength sampled in the rest frame, and because it will cause these dimmest supernovae to fall below the detection limit.

- These two effects are further magnified if the average extinction (at fixed rest frame wavelength) increases with redshift, with the result of systematically biasing the estimated SN rate, recovering only the least obscured events. Again, the effect is maximum in the highest redshift bin.

A direct estimate of the distribution of reddening/extinction, based on the observed UV slopes, was obtained by Daddi et al. (2007) for the ~ 1000 star-forming, $K_{\rm Vega} < 22$ galaxies at $1.4 < z < 2.5$ in the GOODS-South field, with $E(B-V)$ set to zero for passively evolving galaxies. As generally adopted in the study of high redshift galaxies, the extinction law by Calzetti et al. (2000) was used. The K-band limit of this sample corresponds to a $M \gtrsim 4 \times 10^9 M_\odot$ stellar mass limit. To this level, we account for a stellar mass density of $5.3 \times 10^7 M_\odot$ Mpc^{-3}, about 2/3 of the total at $z = 1.8$, integrated over a Schechter function fit in the GOODS-South sample (Fontana et al. 2006). This sample also accounts for a star-formation rate density of 0.12 $M_\odot$ yr^{-1} Mpc^{-3}, close to the (admittedly uncertain) integrated value at $z \sim 1.5$–2 (e.g., Perez-Gonzalez et al. 2005; Hopkins & Beacom 2006). A straight Salpeter IMF is used for these derivations and comparisons. Thus, we believe that this sample of galaxies includes the bulk of the stellar mass and star formation at these redshifts, hence the bulk of SNIa events. Note also that the reddening $E(B-V)$ derived from the UV slope is, in case, biased towards the less obscured regions of a starforming galaxy, since those which have a higher extinction give a small (if any) contribution to the UV flux, hence to the UV slope.

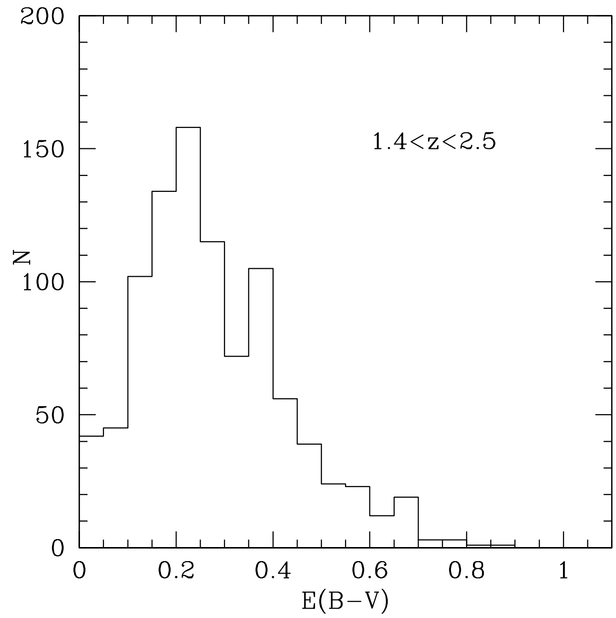

Figure 2. The distribution of reddening among $K_{\rm Vega} < 22$ galaxies at $1.4 < z < 2.5$ in the GOODS-S field (from Daddi et al. 2007). .

Fig. 2 shows the resulting reddening distribution, which peaks at $E(B-V) = 0.2$, not much larger than the average value adopted by Dahlen et al. However, what matters for the SN statistics are primarily the mass-weighted and SFR-weighted average values of $E(B-V)$. Fig. 3 and 4 show, respectively, the reddening $E(B-V)$ vs. the stellar mass and the SFR for each of the galaxies in the GOODS-S sample. The reddening is definitely stronger in more massive, more star-forming galaxies, i.e., in those galaxies that are more productive of SNIa events. Indeed, the mass-weighted and SFR-weighted reddening $E(B-V)$ are respectively 0.36 and 0.41. Fig. 5 shows both the fraction of the stellar mass and of the star formation rate in each reddening bin. Note that $\sim 12.5\%$ of the stellar mass at these redshifts is in passively evolving galaxies with $E(B-V) = 0$. Thus, we adopt $E(B-V) \sim 0.4$ for the average reddening affecting SNIa events at these redshifts, as to a first approximation the SNIa rate depends on a simple linear combitation of galaxy stellar mass and current star formation rate (see Section 3).

As mentioned above, at $z = 1.6$ the F850LP filter samples the 3200 Å in the rest frame, and for the Calzetti et al. (2000) extinction law one has $A_{3200} \simeq 7 \times E(B-V)$, i.e., an average ~ 2.8 magnitudes of extinction for $<E(B-V)>= 0.4$. Adopting instead $E(B-V) = 0.15$ at all redshifts, as in Dahlen et al. (2004), one derives a much smaller average extinction, i.e., ~ 1 magnitude at $z = 1.6$. Therefore, we argue that Dahlen et al. have underesti-

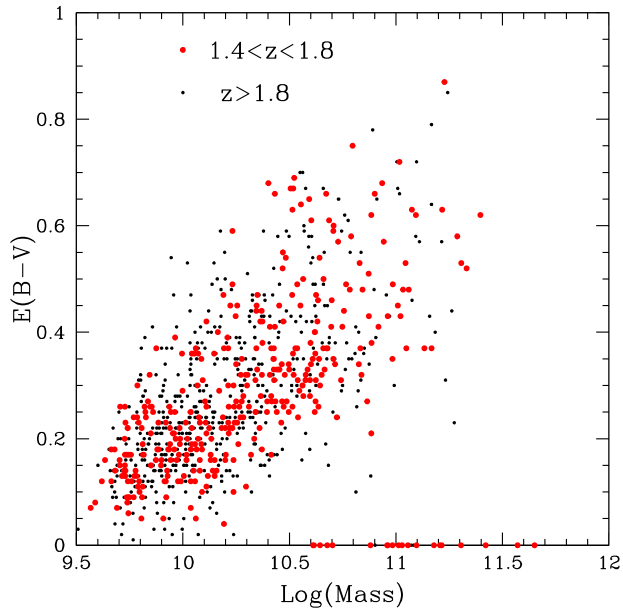

Figure 3. The reddening vs stellar mass (in $M_\odot$ units) for the $K_{\rm Vega} < 22$ galaxies at $1.4 < z < 2.5$ in the GOODS-S field (from Daddi et al. 2007). Galaxies at $1.4 < z < 1.8$ and $z > 1.8$ are plotted with different symbols as indicated in the figure. Note the small group of massive, passively evolving galaxies with $E(B-V) = 0$.

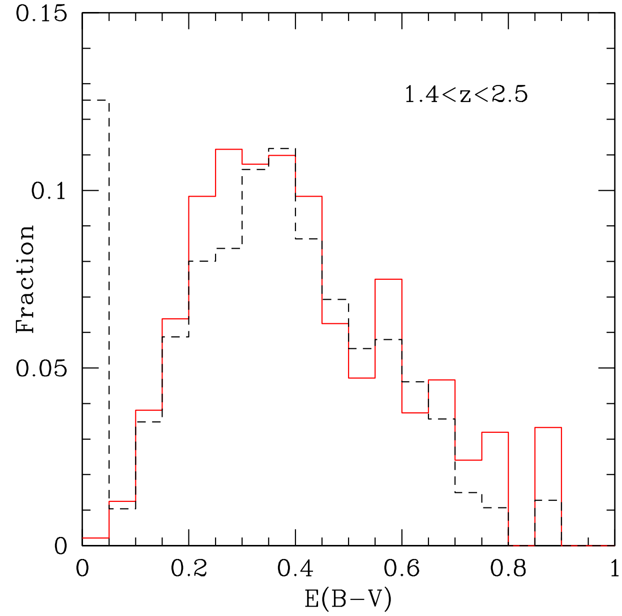

Figure 5. The fraction of stellar mass (dashed histogram) and of the star formation rate (full line histogram) in each reddening bin for the same sample of $1.4 < z < 2.5$ galaxies shown in Fig. 2, 3 and 4. Note the high spike at $E(B-V) = 0$ in the mass distribution, which is due to the passively evolving galaxies. Correspondingly, no such spike is present in the star formation rate histogram.

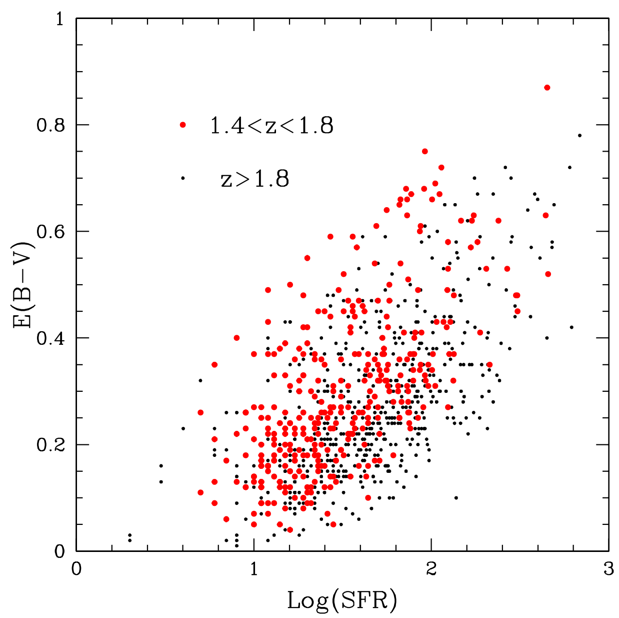

Figure 4. The reddening vs. star formation rate (in $M_\odot$ yr^{-1}) for the $K_{\rm Vega} <$ 22 galaxies at $1.4 < z < 2.5$ in the GOODS-S field (from Daddi et al. 2007).

mated by almost two magnitudes the mass/SFR averaged extinction of galaxies at $z = 1.6$, and have correspondingly underestimated the SNIa rate by a large factor. A quantitative estimate of this effect can be attempted by following the Dahlen et al. prescription according to which a 0.06 error in $E(B-V)$ generates a $1\sigma_{\rm stat}$ error in the estimated SNIa rate. Thus, increasing $<E(B-V)>$ from 0.15 to 0.40, the derived SNIa rate at $z = 1.6$ is going to be higher by $\sim 4\sigma_{\rm stat}$. With the statistical error $\sigma_{\rm stat}$ from Table 2 in Dahlen et al. this corresponds to a factor ~ 4, and therefore by nearly as much was the SNIa rate underestimated. Of course, this is quite a rough estimate of the effect, as the derived rate of SN events does not depend only on the average extinction, but specifically on the full distribution of extinctions (such as shown in Fig. 5), and even on the distribution of extinction within each individual galaxy relative to the observer.

More recently, Dahlen, Strolger & Riess (2008) have analysed an expanded sample of SNIa events over the GOODS fields, bringing the total to 56 events compared to the 23 events in the original GOODS sample. However, the number of events in the highest redshift bin $z = 1.4 - 1.8$ increases only from 2 to 3. All in all, Dahlen et al. (2008) confirm their previous result, i.e., a low rate at $z = 1.6$, having adopted nearly the same assumptions concerning the average extinction as in Dahlen et al. (2004), independent of galaxy mass, star formation rate and redshift. In their recent study, Dahlen et al. discuss the effect of various extinction distributions relative merely to inclination effects, including some with a tail to very high extinctions. All such assumed distributions peak at zero extinction, at variance with the pertinent empirical distributions shown in Fig. 2 and 5. Of course, what matters is the distribution of extinctions affecting specifically the SNIa events, which may differ from the distribution of average extinctions affecting galaxies as a whole. However, we conclude that Dahlen et al. (2004, 2008), having strongly underestimated the average extinction of high redshift galaxies, are likely to have underestimated by a large factor the SNIa rate at $z = 1.6$. Therefore, there remains little ground for the extremely *tardy* DDT function inferred by Strolger et al. (2004, 2005).

3 THE TWO-COMPONENT DDT

Scannapieco & Bildsten (2005) propose a crude, yet effective representation of the SNIa rate in galaxies, with a component proportional to the mass in stars, and another to the current SFR:

$$R_{\rm Ia}(t) = AM_*(t) + B\dot{M}_*(t). \quad (1)$$

In practice, the implied DDT(t) is the sum of a Dirac's delta at $t = 0$ and a constant, representing respectively a *prompt* and a *tardy* component, i.e., $DDT(t) = \delta(0) + \mathrm{const}$. Counting on the two adjustable parameters A and B, this simple rendition of the DDT function can quite satisfactorily reproduce several SN related properties of stellar systems, such as e.g., the correlation of the SNIa rate with galaxy colour in the local universe, the SNIa rate history of star-forming galaxies, the origin of the α-element enhancement in spheroids, etc.. However, it certainly fails in other astrophysical situations. For example, it implies a non-evolving SNIa rate in passively evolving galaxies, in which the cumulative number of SNIa's increases linearly with time, hence a diverging productivity of SNIa's for a finite mass in stars. At the same time, passively evolving (SFR=0) galaxies of given mass, but vastly different ages would have the same SNIa rate according to Eq. (1), contrary to the empirical evidence in Totani et al. (2008). Therefore, formulation (1) can only be applied to a limited number of concrete situations, and can produce invalid results in others.

The SNIa rate in galaxies is the convolution of the DDT with the star formation history (SFH):

$$R_{\rm Ia}(t) = \int_0^t \mathrm{SFR}(t-t')\,\mathrm{DDT}(t')\,\mathrm{d}t' \quad (2)$$

having indicated with t' the delay time. By splitting the integration over short (*prompt* component) and long delay times (*tardy* component), this equation reduces to Eq. (1), with B proportional to the fraction of *prompt* events, and A proportional to the SFR-weighted-DDT, averaged over the *tardy* events. Hence, when fitting relation (1) to a set of data, B will depend on the time span assumed for the prompt events, and A on the adopted law for the SFH (besides the shape of the DDT). Indeed, very different values for the A and B *constants* are found in the literature **(**Scannapieco & Bildsten 2005; Sullivan et al. 2006; Neill et al. 2006), with with B values that differ up to a factor of $\sim$ 5. Whereas part of the discrepancies are due to the different quality of the various data samples, the application of Eq. (1) naturally results into a dependence of A and B on the (arbitrary) choice of the time delay separating *prompt* from *tardy* events, and on the actual SFH of the galaxies in the samples. This is to say that A and B cannot be universal constants.

The shortcoming with relation (1) is that it does not adequately describe the contribution to SNIa events at intermediate delay times, and the prompt events are completely attributed to the ongoing SF. While this is correct in the case of core collapse (CC) SNe, there's no reason to hold this true for SNIa as well. The existence of a channel for SNIa closely related to the current SFR was also suggested in Mannucci et al. (2005), having noticed that in star forming galaxies the SNIa rate varies nearly in locksteps with the rate of CC supernoave. Actually, the ratio of the CC to the SNIa rates increases as the galaxies get bluer or of later type, especially from Sa to Sc (Mannucci et al. 2005), indicating that also in very actively star-forming galaxies SNIa events lag behind CC events.

4 DDT MOTIVATED BY THE SNIA RATE IN RADIOGALAXIES

Mannucci et al. (2006) have advocated a *bimodal* DDT, with the *prompt* and *tardy* components being physically distinct or even separated in time. The driving argument for the bimodality follows from the excess SNIa events that is observed in a sample of radio-loud elliptical galaxies, with respect to radio-quiet galaxies of the same morphological class (Della Valle et al. 2006). This is a $\sim 2\sigma$ excess, that Della Valle et al. ascribe to star formation having been triggered by the same merging/accretion event powering the nuclear activity in radio-loud galaxies, whose duration is assumed to be $\sim 10^8$ years. The consequence of this interpretation, is a favored DDT function in which $\sim$ 50% of all SNIa's explode within the first $\sim 10^8$ yr after a star formation episode (the prompt component), and the rest are distributed over the following many Gyr (the tardy component). Taken quantitatively at face value, this inferred DDT function would have quite important consequences for constraining the nature of the progenitors, excluding most of otherwise plausible models, see for example Fig. 13 in Greggio (2005). For this reason, we take the liberty of re-discussing here the Della Valle et al. interpretation of the SNIa excess in radio-loud ellipticals.

We first quantify this excess. In the sample analysed by Della Valle et al., 7 SNIa's were found among the radio-quiet ellipticals, and 9 among the radio-loud ones, with an additional SN having exploded in a galaxy with borderline radio power, hence it was attributed for one half to the radio-quiet group and one half to the radio-loud group. The relative normalized control times (the product of the time during which a galaxy was monitored times its B-band luminosity) were cumulatively 7127 and 2199 (yr$\times L^{\rm B}_{\odot}/10^{10}L^{\rm B}_{\odot}$), respectively for the sample of radio-quiet and radio-loud galaxies. Thus, if the productivity of SNIa events was the same regardless of radio power, one would have expected to find $\sim 2199 \times 7.5/7127 = 2.3$ SNIa's in the radio-loud sample, while instead 9.5 have been observed. There was therefore a sizable excess of $\sim$ 7 events, that Della Valle et al. attribute to a recent star formation episode. In terms of SN rates, they infer a SNIa rate of $0.43^{+0.19}_{-0.14}$ SNU for the radio-loud galaxies, and $0.11^{+0.06}_{-0.03}$ SNU for the radio-quiet ones (1 SNU = 1 SN per century per $10^{10}L^{\rm B}_{\odot}$).

Della Valle et al. (2006) argue that if the excess SNIa events is due to recent star formation in radio-loud galaxies, then they should be accompanied by a corresponding share of core collapse (CC) supernovae, given that in star forming galaxies CC supernovae outnumber the SNIa's 8 to 3. However, no CC supernova has been found in the whole sample of radio-loud galaxies. Della Valle et al. argue that this is not in contradiction with their star formation hypothesis, since they calculate that only less than one (i.e., 0.62) CC supernova should have been found. We believe that their calculation is not correct, and repeat it here, based on the same input numbers. We estimate the number of CC supernovae that should have resulted from the same star formation event responsible for the excess SNIa's in the following way:

$$N_{\rm CC} = \frac{R_{\rm CC}}{R_{\rm Ia}} \cdot N_{\rm Ia} \cdot \frac{CT_{\rm CC}}{CT_{\rm Ia}}, \quad (3)$$

where the ratio of the two SN rates is taken as 8/3, the number $N_{\rm Ia}$ of excess SNIa's is 7, and the ratio of the two control times is 4057/2199=1.84 in favor of CC supernovae. The result is that 34 (!) CC supernovae should have exploded, but none was observed. The discrepancy with the $\sim$ 30 times smaller estimate by Della Valle et al. stems from them having multiplied this number (34), by 0.03, the ratio of the maximum lifetime of CC supernova progenitors (30 Myr) to an assumed duty cycle between successive

episodes of nuclear radio activity (1 Gyr). Multiplication by this factor is not appropriate, as neither the lifetime of CC supernova progenitors, nor the radiogalaxy duty cycle have any connection with the observability of the predicted 34 events. Moreover, the 8/3 CC/SNIa ratio pertains to steadily starforming galaxies, in which the full range of delay times contribute to the SN rates. In this particular case, the 7 *excess* SNIa events are assumed to belong to an extremely prompt component, that would contribute some $\sim$ 50% of all events, and therefore the appropriate CC/SNIa ratio should actually be twice as large, i.e., $\sim 16/3$, implying that the 7 SNIa events should have been accompanied by $\sim 69 \pm 26$ CC events. The Della Valle et al. sample of 267 radio loud galaxies can be regarded as a unique entity having experienced continous star formation over the last $\sim 10^8$ years, even if star formation occurred in bursts within individual galaxies. Thus, Eq. (3) (without further reducing factors) gives the total number of CC events that should have been observed within the sample of radiogalaxies. Failing to detect so many CC events could result if galaxies in the act of a starburst, or during the on phase of CC supernovae, would not qualify as radiogalaxies according to the criterion adopted by Della Valle et al. (2005), as if radio activity would develop only after star formation (and CC supernova events) had subsided. Instead, starburst and radio activity are often simultaneus phenomena, as e.g., in the prototypical case of NGC 1275 (Gallagher 2007). It seems quite unlikely to us that such decoupling of radio activity and CC supernovae could be so extreme as to have all predicted CC events occurring outside of the radio loud phase of galaxies.

We conclude that if the 7 excess SNIa events in the monitored sample of radiogalaxies were due to recent star formation then a much larger number of CC supernovae should also have been detected in the sample of radio-loud galaxies. Since none was observed, we argue that it is quite unlikely that the 7 events were due to starbursts that would have occurred in the last $\sim 10^8$ years. Starbursts may well have occurred in the sample of radiogalaxies, but likely involved a stellar mass insufficient to produce the excess SNIa events, as also indicated by the colours of radio-loud galaxies (in given mass bins) being indistinguishable from those of radio-quiet galaxies (Mannucci 2007; see also Johnston et al. 2008). Recent bursts of star formation in radiogalaxies as reponsible for their excess SNIa events is also excluded by Cappellaro, Botticella & Greggio (2007), based on the relative frequency of CC and SNIa events.

Having excluded star formation, the question remains of the origin of the observed excess. One quite plausible possibility is just small number statistics: after all the excess is only a 2-σ effect, and could well disappear in future, wider SN surveys.

5 SNIA BIMODALITY AND CO-EXISTENCE OF SD AND DD PROGENITORS

While excluding the kind of bimodality motivated by the apparent SNIa excess in radio-loud galaxies, recent observations suggest that a substantially different kind of bimodality may actually exist. Indeed, as mentioned in Section 1, there is now direct evidence for nature using both the SD and the DD channels for producing SNIa events, although the relative contribution of the two channels remains substantially unconstrained. The DDT functions for the SD and DD cases depend on partly different physical ingredients: the nuclear lifetime of the secondary star in the binary progenitor for the SD case, with the addition of the gravitational wave radiation delay for the DD case. Therefore, following a star formation episode, the relative contributions of the two channels is going to change with time, and so will their mix as a function of cosmic time when convolved with the cosmic history of star formation.

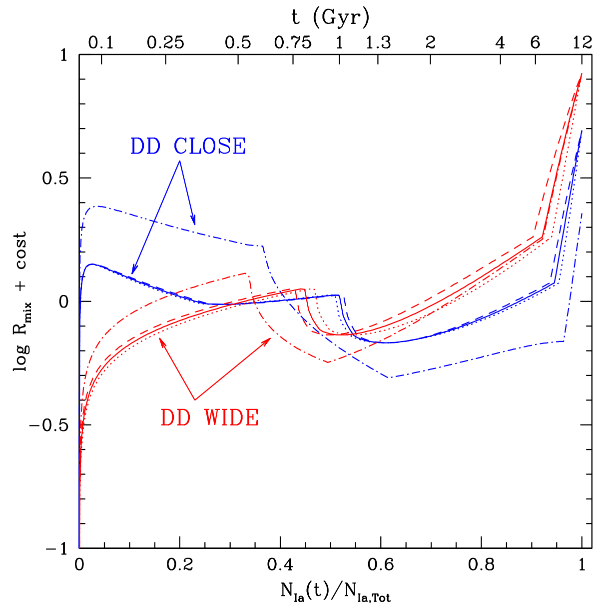

Figure 6. Ratio of the rates from the DD and the SD channel as a function of the fraction of SNIa events occurred in an SSP, for the same models shown in Fig. 1 and with the same line encoding. The solid and dot-dashed curves illustrate the case in which the SD and DD channels contribute equally to the total number of SNIa events up to t = 12 Gyr (this corresponds to *const* = 0 on the vertical axis of the figure). The effect of a different partition between SD and DD events is shown for the solid lines models, as dotted and dashed curves, which plot respectively the results for a 30% (*const*=+0.37) and 70% (*const*=-0.37) contribution of the DD channel. Note that a different partition essentially shifts the lines along the vertical axis, while the effect on the horizontal axis is small. The upper axis is labelled with the age of the SSP for the case of a 50% contribution from the two channels, and the DD CLOSE model shown as a solid line. The correspondence between the age of the SSP and the fraction of events is somewhat different for the other cases.

5.1 The evolution of the SNIa mix

In this section we explore how the relative importance of DD and SD events may vary with the age of a stellar population, as well as over the cosmic time. If the two SNIa channels produce events with different observational characteristics (e.g., luminosity at maximum, colour, rate of decline, etc.) a secular variation of the ratio of their rates impacts on the properties of observed samples, and may potentially introduce a systematic bias on the estimated distances. The exploration is made by using the DDT functions for the sample of SD and DD models shown in Fig. 1. We emphasize that our conclusions are not affected by the specific selection of these models, but rather reflect their generic properties.

Fig. 6 shows the ratio R_{mix} between the SNIa rates for DD and SD models in a simple stellar population (SSP) as it ages up to 12 Gyr. The ratio is plotted as a function of time since the star formation episode (upper scale), as well as against the running number of SNIa events occurred in the system up to a given time t (lower scale), normalized to the total number of events up to t = 12 Gyr. Common to all the explored cases is that at first the SD channel pre-

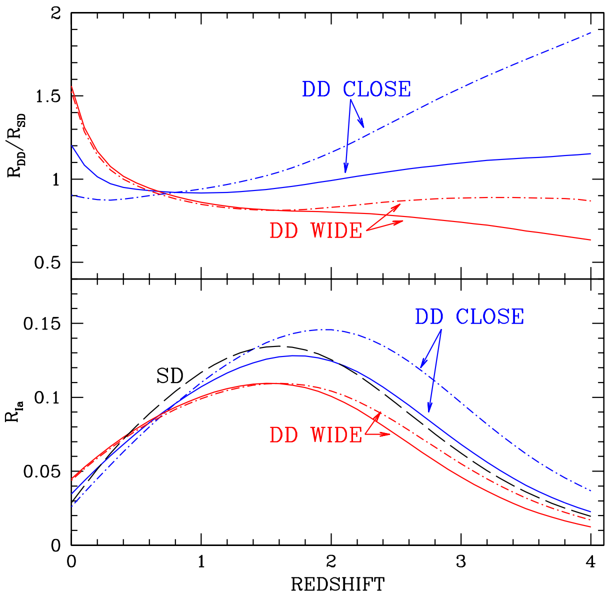

Figure 7. The cosmic evolution of the SNIa rates, and of their ratios, predicted for the model DDTs shown in Fig. 1. The adopted cosmic star formation history is from Hopkins and Beacom (2006), case Sal-A, Cole function up to a redshift of 6, when star formation is assumed to start. The linetype encoding for the DD models is the same as in Fig. 6; the bottom panel shows the evolution for the SD model as a dashed line.

vails, but the rate from DD explosions rapidly increases and catches up relative to the SD events. This occurs over a time scale which is very short ($\lesssim$0.1 Gyr) in the DD CLOSE case, characterized by strong orbital shrinkage during the common envelope episodes of the progenitor binary (Greggio 2005). This time is a little longer ($\sim$ 0.5 Gyr) in the DD WIDE case, where less orbital shrinkage is assumed, and therefore gravitational wave radiation takes longer to bring the two WDs into contact.

At later times the ratio of the two rates levels off, and resumes to grow rapidly when the SSP ages through the second cusp in the SD DDT, i.e. for $t \gtrsim 8$ Gyr (see Fig. 1). This cusp is due to the requirement of reaching the Chandrasekhar limit, which at a late epoch remains possible only for binaries with more and more massive WD primaries.

All in all, the ratio varies by about 2 orders of magnitude in the 0–12 Gyr time interval, with SD events dominating at (very) early times, and DD events largely dominating at (very) late times. However, during most of the time the ratio of the two rates is actually confined within $\sim \pm 40\%$ of its average value. This constant mix of the SNIa events from the two channels is even more so if we consider the central 90% of the events, i.e. cutting out the 5% events at early times and the 5% events at late times.

Thus, we do not expect dramatic differences in the SD/DD mix of SNIa samples in star-forming galaxies. However, in galaxies which have evolved passively for a time comparable to the Hubble time, such as elliptical galaxies, the SD-SNIa rate may have already entered its very fast final drop seen in Fig. 1 and, correspondingly, most (if not all) SNIa's in these galaxies may result from the DD channel which is able to remain active for a much longer time. This would be even more so if the accretion efficiency for the SD systems is smaller than unity. Note that for galaxies that have been passive over the last 10-12 Gyr, the evolution of the SNIa rate follows closely the DDT functions for a single burst which are shown in Fig. 1, i.e., much different from the constant rate over time implied by the parameterization of Scannapieco & Bildsten (2005).

The five SNIa distributions of delay times shown in Fig. 1 have also been convolved with the cosmic history of star formation in its analytic rendition proposed by Hopkins and Beacom (2006). The results are shown in Fig. 7 (lower panel), along with the corresponding evolution with redshift of the ratio between the DD and SD rates (upper panel), in the case of an equal contribution of the two channels to the cumulative number of events all the way to $z = 0$. If the cumulative contributions are different, the scale changes by a multiplicative factor, but the relative evolution of the ratio remains the same.

The behaviour of the ratio with redshift is different for the DD CLOSE and the DD WIDE models: in the latter case, the increased importance of the long delay time events results in a high contribution of DD explosions at low redshift. In the DD CLOSE models, instead, the DDT function is comparatively steeper at late times (cf. Fig. 1), so that their contribution is less pronounced at low z. If the DDT is sufficiently steep (dot-dashed line), the DD events happen to dominate even at high redshift.

In conclusion, Fig. 7 (upper panel) shows that the expected evolution with redshift of the SD/DD mix is rather mild. Within the range currently explored by observations ($z < 1.8$) the largest variation is exhibited by the combination DD-WIDE/SD, where the corresponding mix drops by $\sim$ 60% between $z = 0$ and 1.

In principle, the redshift evolution of the SNIa mix may have important implications for the systematic effects it could induce on the distances inferred from the SNIa luminosity, and implied rate of cosmic acceleration. Thus, the relatively modest variation with redshift of the SD/DD mix is quite reassuring. However, we caution that even within each of the two channels the distribution of the properties of the SNIa progenitors are expected to change with redshift in a systematic fashion. This is the case because at high redshift only relatively "prompt" events can take place. Thus, progenitor properties such as the age of the primary WD, or the combined mass of the two WDs in DD systems, etc. are characterized by distribution functions that vary with redshift, thus potentially having an effect on the SN explosion, light curve, luminosity, etc. For example, the age of the primary WD controls its internal temperature stratification, and the extent to which crystallization and/or carbon-oxygen diffusive separation have taken place inside the WD prior to the SN explosion. In turn, these properties of the progenitor system may affect the explosion itself, hence the light-curve, and indeed it is well known that SNIa's exhibit a range of peak luminosities. It is also well known that peak luminosity and shape of the light curve (specifically, it rate of decline) correlate closely, and therefore these variations are corrected for when using SNIa's for distance determinations (e.g., Riess 1998). However, it remains to be empirically established whether the local calibration of the relation between luminosity and rate of decline holds true also at high redshifts.

5.2 Predicted evolution with redshift of the SNIa rate

Fig. 7 (lower panel) shows the evolution with redshift of the SNIa rate for each of the 5 DDT functions shown in Fig. 1, having convolved the latter ones with the cosmic SFH from Hopkins & Beacom (2006). The generic expectation from both SD and DD models is an increase of the rate with redshift by a factor 3–4 between $z = 0$ and $z \sim 1$, in fair agreement with current empirical estimates, e.g. as reported by Dahlen et al. (2008). However, this increasing trend

continues up to $z = 1.6 - 2$, while the empirical rate by Dahlen et al. (2004, 2008) drops to a low level at $z = 1.6$. Note that a peak SNIa activity at $z \sim 2$ is predicted also by other SD models for the SNIa precursors, that include as possible precursors WD+ main sequence star systems (Kobayashi, Tsujimoto & Nomoto 2000). The reasons for the apparent drop at $z = 1.6$ have been already discussed, and we believe that the key issue is the extinction in real galaxies at this redshift being ~ 2 magnitudes higher in the rest frame than assumed by Dahlen et al.. Deeper z-band observations would be needed to vindicate or exclude the SD/DD model predictions for $z > 1.4$ shown in Fig. 7. Even better, deep near-IR observations would sample rest-frame wavelengths less affected by internal extinction. A first opportunity will still be offered by HST, which after the next Servicing Mission will provide deep H-band imaging with WFC3, thus probing the rest-frame ~ 6000 Å at $z = 1.6$, and ~ 5300 Å at $z = 2$. Exploring the declining SNIa rate beyond redshift ~ 2 should be possible with future JWST observations at wavelengths longer than 2 μm, that at these redshifts will sample the relatively unobscured rest-frame I band.

6 CONCLUSIONS

We have examined the empirical basis for the very *tardy* distribution of SNIa delay times advocated by Strolger et al. (2004), derived from the SN rate as a function of redshift measured by Dahlen et al. (2004) over the GOODS fields. Critical to this derivation is the last data point at $z = 1.6$. We show that the adopted extinction effect at this redshift has been strongly underestimated compared to actual measurements of the extinction for a representative sample of galaxies at the same redshift derived from the GOODS database (Daddi et al. 2007). The assumption of extinction in high-redshift galaxies being the same as locally clearly conflicts with all available evidence, in particular when considering that galaxies at $z \gtrsim 1$ and $z \sim 2$ form stars at a factor of ~ 10 and ~ 30 higher rate, respectively, compared to local galaxies (e.g. Elbaz et al. 2007; Daddi et al. 2007) and have much higher gas fractions (Bouché et al. 2007; Daddi et al. 2008), and ULIRGs are ~ 1000 times more numerous than locally (Daddi et al. 2005). Thus, we conclude that there is at present no physical ground for the Strolger et al. distribution of delay times, which suppress virtually all SNIa events for delay times less than ~ 2 Gyr. Deep HST observations in the near infrared are needed to properly measure the SNIa rate at $z \gtrsim 1.4$.

At the opposite extreme, we examine the very *prompt* distribution of delay times advocated by Mannucci et al. (2006), based on a putative excess of 7 SNIa events in a sample of radiogalaxies. This excess is attributed to minor episodes of star formation concomitant with the activation of nuclear activity in radiogalaxies. We argue that if the 7 excess SNIa events were due to recent bursts of star formation in radiogalaxies, then over 30 core collapse supernovae should have exploded within the monitored sample of radiogalaxies, but none was actually observed. We conclude that the excess SNIa events are unlikely to be due to recent star formation, and may just be the result of small number statistics, the excess being indeed only a 2σ effect. Thus, there appears to be no physical basis for the very prompt distribution of delay times advocated by Mannucci et al. (2006).

Having excluded these mutually irreconcilable renditions of the SNIa distribution of delay times, we recall that theoretically motivated renditions for these distributions, for either the so-called single degenerate (SD) or the so-called double degenerate (DD) channel, quite naturally predict distributions of delay times with both a prompt as well as a late component. Being these distribution controlled by partly different physical effects in the SD and DD channels, the SD/DD mix of SNIa's is predicted to vary in a systematic fashion as a function of cosmic time (redshift). This effect is illustrated for selected samples of SD and DD models, indicating that the SD/DD mix of SNIa events is not expected to vary more than $\sim 50\%$ over an extended period of cosmic times and redshifts. This is on the reassuring side when using SNIa's as standard candles for the determination of cosmological parameters.

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Note added in proof It is possible that in Section 4 we have overestimated the number of core collapse (CC) supernovae expected in the sample of radiogalaxies if the 7 excess SNIa events are due to recent star formation. Della Valle et al. (2005) derive their estimated number of CC events (0.62) originated from the postulated star formation as the product of an expected rate of CC SNe (0.0152 h^2_{75} SNu) times a control time (4057/100), and since star formation was associated to radio loudness, we interpreted both quantities as pertaining to the radio loud galaxies. If instead rate and control time were meant for the whole sample of ellipticals (irrespective whether radio loud or not), the control time for radio loud galaxies only should be lower than adopted in our calculation. Della Valle et al. do not explicitly report the CC control time for the radio loud galaxies, but to first order it is $(2199/11096) \times 4057 = 804$, where 2199 is the SNIa control time for radio loud galaxies, and 11096 is that for the entire sample. This assumes the fraction of control time for radio loud galaxies to be the same for both CC and Type Ia supernove, which is justified by the observational database being the same for both SN types. If so, our estimated number of expected CC events among radio loud galaxies (69) has been overestimated by a factor ~ 5, hence should rather be ~ 14 events, still ~ 20 times higher than estimated by Della Valle et al (2005). We maintain our conclusion that the lack of observed CC events remains a challenge for the interpretetation of the 7 excess SNIa events in terms of recent star formation. We are grateful to Massimo Della Valle for having pointed out to us our misinterpretation of their CC control time.